Inst. Phys. Conf. Ser. No. 148, pp 423-426
Paper presented at Applied Superconductivity, Edinburgh, 3-6 July 1995

Low Field Magnetization Nondestructive Evaluation of HTS Tapes within the Bean Critical State Model

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Abstract. A new approach, that accounts for demagnetization, is described for calculating the flux front boundary within the Bean critical state model for a tape geometry. The method combines an analytical description in the form of an integral equation for the flux front boundary with a numerical method of resolving that equation. Results are given for a source coi above the tape and measuring coils above and below .

1. Introduction

Quantitative determination of the local low field critical current density, $J_C(H=0)$, in a noncontacting manner is useful in the fabrication of high temperature superconducting (HTS) tapes as a nondestructive evaluation (NDE) probe of processing parameters and spatial uniformity. Transport critical currents are most often measured by contact 4-point probes; however, noncontacting magnetic measurements are desired in many practical situations for their speed and ease of use. The magnetic approach consists of measuring the induced currents in the sample with small source/pickup probe coils that spatially scan over the tape surface [1,2]. Subsequently, the Bean critical state model is relied on to determine J_C from the measured magnetic hysterisis. This approach provides a measure of the critical current density since the intergrain critical current density is usually much smaller than that for intragrain.

Usually, the Bean model is used in a context which ignores sample geometry effects, referred to as demagnetization, due to the intractibility of the calculations required. Plate geometries present the most severe demagnetization effects for external fields directed perpendicularly to the surface. Certain geometries, such as a cylindrically symmetric sample in a uniform field, can be treated by numerical methods [3]. Another approach treats the plate by averging the current distribution over the thickness of the plate and thereby obtains an analytical solution [4].

A new approach is described that combines an analytical description of the problem in the form of an integral equation for the flux front boundary with a numerical method of resolving that equation [5]. This method is applicable in cylindrically symmetric geometries for both the external field and the sample. It can be used to determine the critical state region profile including the effects of demagnetization. The integral equation method has been applied to a sphere in a uniform external field [5] and a plate in a cylindrically normal field [6,7] This paper describes resaults from the integral equation method for the plate geometry along with experimental measurements on silver clad Pb-BSSCO (2223) tapes. Results are presented for a measuring coil parallel to the source coil above and below the tape for a given local critical current density J_C

2. Calculation of the Flux Front Surface

The source coil above the tape generates a flux front that penetrates into the tape. Eventually, at high excitation currents, this front penetrates completely through the tape and splits into two fronts as shown in figure 1. The approach taken is to calculate the location of the flux fronts based on the shielding ability of the screening currents to produce a region of zero magnetic field below the front. This idea leads to an integral equation for the font location that can be solved by a numerical iteration scheme [8]. The details of the method of solution have been presented elsewhere [4,5]; calculation results and measurements are described here. Exploiting cylindrical symmetry, an integral equation can be written for the flux front, an integral equation can be written to determine the flux front profile as follows:

$$\Psi(R,\beta = {}^{I}\!\big/_{J_C r_C^2}),\int_0^\infty dR' a_\phi(R,\Psi(R,\beta);R',\Psi(R',\beta))\frac{-\partial\Psi(R',\beta)}{\partial\beta} = a_\phi(R,\Psi(R,\beta);1,Z_c)$$

where $\mu_0 a_\phi(R,Z;R',Z')$ is the vector potential at *(R,Z)* due to a unit current coaxial loop of radius *R'* at height *Z'*. The coil radius is r_C, J_C the local critcal current density and I the source coil current. This integral equation can be resolved for the flux front derivative knowing the flux front profile for some initial value of the external field. Since the starting flux front profile for zero external field is just the sample surface, equation 1 provides an incremental numerical scheme for determining the the profile for any external field [5-7]. When the external field becomes large enough for the flux front to reach the bottom plate surface, the front breaks up into two separate profiles. Continuation of the method results in a pair of integral equations that are resolved simultaneously by the same algorithm as with the single profile [6,7].

Once the flux front location is known, the total vector potential, and measured signal can be determined for a pickup coil in any position. Figure 2 shows the signals predicted for pickup coils above and below the plate, where the external field is subtracted off above (balanced) and included below (unbalanced). Particularly, the pickup signal below the tape reflects the screening brought about by currents flowing at less than the local critical current density and forms a good indicator of local tape condition. The curves of figure 2 are obtained by incresing the external field starting from the zero field cooled state. Complete hysteresis loops, for cycles of the external field, can be obtained for each pickup coil position and are shown in figures 3 & 4. Significantly different hysteresis loops are found for the top and bottom coils due to the screening currents in the tape.

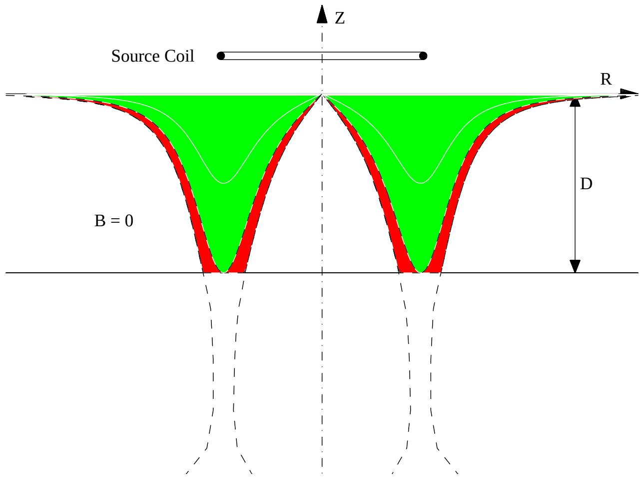

Figure 1. Calculated flux fronts penetrating a tape of thickness D generated by a source coil above.

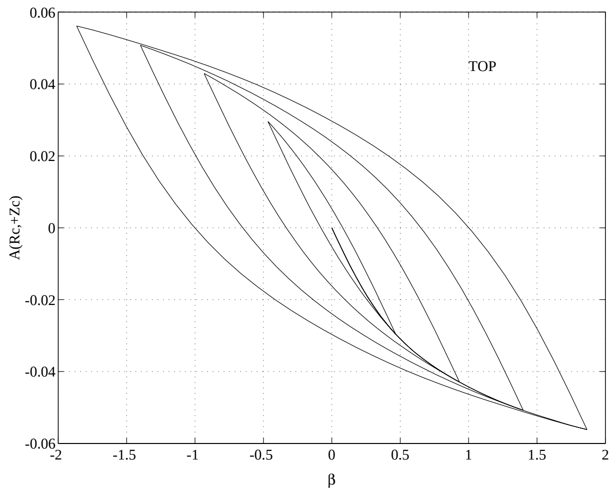

Figure 2. Calculated pickup signal amplitudes for a top balanced pickup coil and a bottom unbalanced pickup coil.

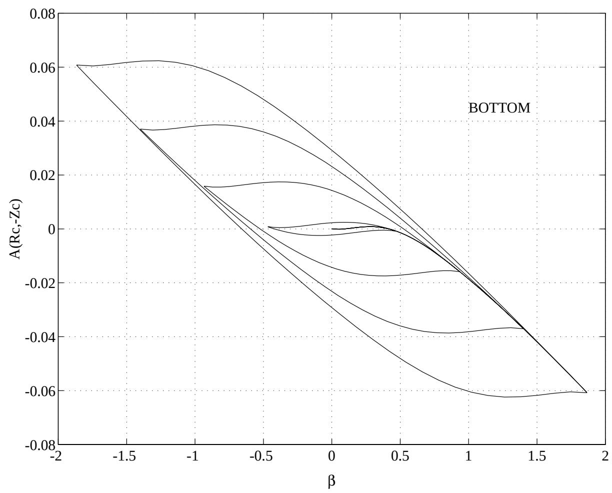

Figure 3 Hysteresis loops at the top balanced pickup coil for several maximum external field values

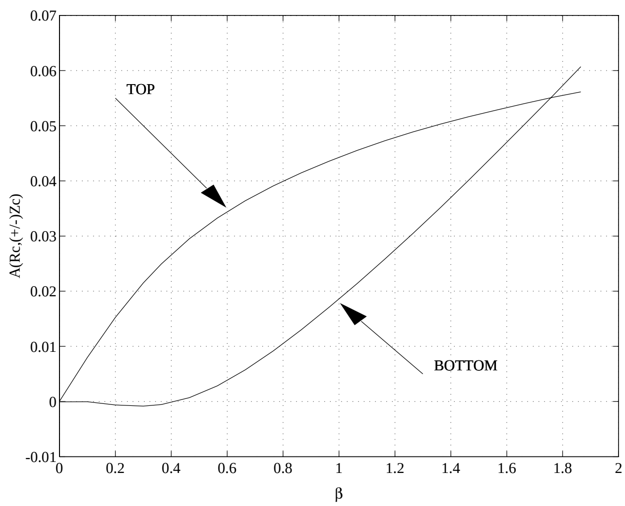

Figure 4 Hysteresis loops at the bottom unbalanced pickup coil for several maximum external field values.

Using the prescription of the Bean critical state, the complete hysteresis response is calculated from $A_{\pm}(R,Z;\beta) = \pm A_0(R,Z;\beta_{\max}) \mp 2A_0(R,Z;\frac{\beta_{\max} \mp \beta}{2})$, where $A_0(R,Z;\beta)$ is the initial curve shown in figure 2. In general β is a function of time; however, only the quasi-stationary states of the critical state are dealt with in this paper. The time scale for changes in the external field is typically very much longer than that exhibited by flux line motion, so the model always assumes a sequence of stationary states uniquely defined by the history and present value of the external field.Therefore, if the time dependence of β is given, the resultant time dependence of both pickup coil signals can be calculated. Figure 5 illustrates this result for the case of a triangular external field time dependence and the maximum values given in figures 3&4. Again, most og the significant changes in the signal waveforms occur for the bottom coil as the flux front penetrates the plate thickness. Harmonic analysis of these signals could lead to a simple method for monitoring the local critical current density through waveform processing.

3. Experimental Measurements

The measurement geometry consisted of a single layer superconductor plate deposited between two outside silver layers. Tape samples of Pb-BiSrCaCuO (2223 phase) produced by the powder-in-tube method [2,9] were measured with a small probe source coil (13 turns of #36 copper wire, 1 mm inside diameter). Balanced opposing pickup coils (5 turns each of #36) were wound over the source coil, producing a small source/pickup probe that could be scanned over the sample surface. An additional pickup coil (5 turns #36 copper wire on 1 mm diameter) was positioned below the tape sample. Lift-off distances for both top and bottom coils were about 0.7 mm. Results are presented below for one measurement position on the tape.

Figure 6 shows the measured results from the top balanced coil at one position on the tape for three different temperatures. These results, which are qualitatively similar to the theoretical results of figure 2, represent the magnetization due only to the induced screening currents within the flux front. No single obvious point signifies the full flux penetration value with which the critical current density can be determined. The results from the bottom coil are significantly different. The shielding effect is nearly complete when the external field is insufficient to cause full plate penetration as shown in figure 7. The shielding effect is clearly visible and, by extrapolation, a unique point corresponding to full plate penetration can be estimated. The local critical current density can then be determined from the corresponding value of β

Conclusions

A method has been outlined for calculating the flux front profile for a superconducting sample in either a uniform or nonuniform applied magnetic field possessing azimuthal symmetry. This technique relies upon finding a surface with zero vector potential. This surface is determined by simple integration of its derivative with respect to the external field, found by resolving a linear integral equation of the first kind. Measurement induced voltages and the entire hysteresis loop response can be found by extension of the ZFC magnetization response with changing external field. Other experimentally measured quantities relating to the critical state can be calculated directly from the hysteresis loop if the time dependence of the external field is known.

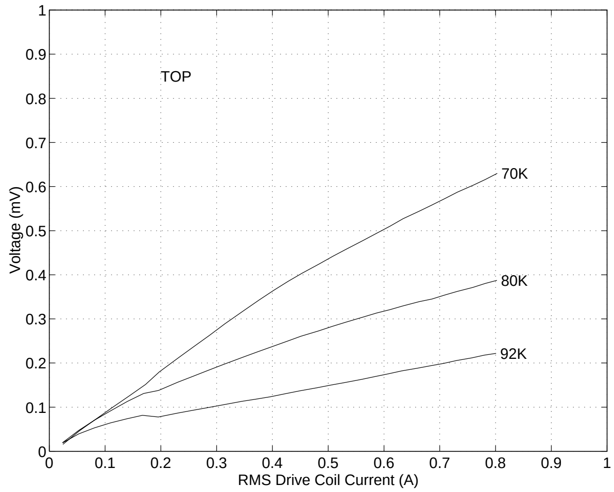

Figure 6 Top balanced coil measured signal amplitudes for different temperatures.

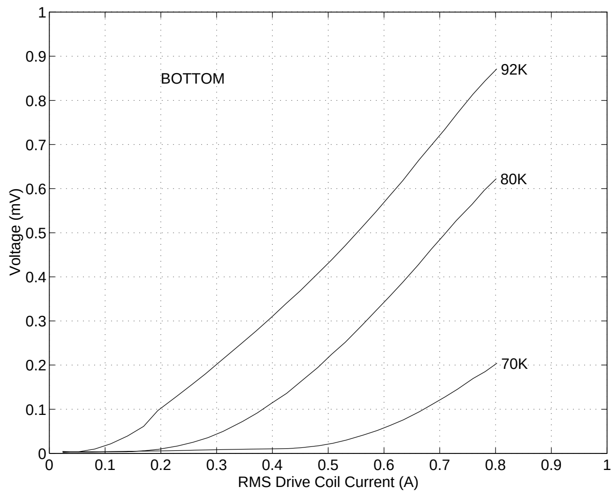

Figure 7 Bottom coil measured signal amplitudes for different temperatures.

Acknowledgment

The authors thank M. T. Lanagan of Argonne National laboratory for the tape samples. This work was sponsored by the U.S. Department of Energy, Office of Energy Research, Office of Basic Energy Sciences, under DOE Idaho Operations Office Contract DE-AC07-94ID13223.

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